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Joe Craft
United Space Alliance

Don Sauvageau
ATK Thiokol Propulsion

Robert Ess
NASA Johnson Space Center

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Joe Craft
United Space Alliance
Houston, TX

Robert Ess
NASA Johnson Space Center
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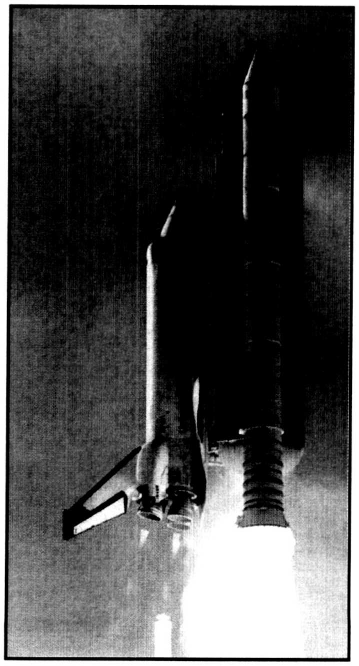
Don Sauvageau
ATK Thiokol Propulsion
Brigham City, Utah

ABSTRACT

The Five-Segment Booster design concept was evaluated by a team that determined the concept to be feasible and capable of achieving the desired abort-to-orbit capability when used in conjunction with increased Space Shuttle main engine throttle capability. The team (NASA Johnson Space Center, NASA Marshall Space Flight Center, ATK Thiokol Propulsion, United Space Alliance, Lockheed-Martin Space Systems, and Boeing) selected the concept that provided abort-to-orbit capability while:
1) minimizing Shuttle system impacts by maintaining the current interface requirements with the orbiter, external tank, and ground operation systems; 2) minimizing changes to the flight-proven design, materials, and processes of the current four-segment Shuttle booster; 3) maximizing use of existing booster hardware; and 4) taking advantage of demonstrated Shuttle main engine throttle capability. The added capability can also provide Shuttle mission planning flexibility. Additional performance could be used to: enable implementation of more desirable Shuttle safety improvements like crew escape, while maintaining current payload capability; compensate for off nominal performance in no-fail missions; and support missions to high altitudes and inclinations. This concept is a low-cost, low-risk approach to meeting Shuttle safety upgrade objectives. The Five-Segment Booster also has the potential to support future heavy-lift missions.



INTRODUCION

NASA has been aggressively pursuing approaches to improving the safety and reliability of the Space Shuttle system. One of the methods that has been evaluated over the past number of years is the development of a five-segment booster (FSB) that enhances the overall safety and reliability of the Shuttle system by minimizing the need to fly the more challenging return to launch site (RTLS) and transoceanic abort landing (TAL) profiles (see references 1 through 4). The initial evaluation of the FSB concept was conducted in 1996 to determine the feasibility of the FSB in achieving TAL from the pad, thus eliminating the RTLS abort mode. This initial study was conducted by ATK Thiokol Propulsion and did show the potential for the FSB to eliminate the RTLS abort mode. Later, Rockwell (now Boeing) conducted a similar study utilizing FSB performance characteristics and verified that the FSB could indeed achieve TAL from the pad, thereby eliminating the necessity for the RTLS abort.

FEASIBILITY STUDY

As a result of the benefit provided by the FSB, Congress provided money to NASA to initiate a Phase A feasibility study to assess and mature the basic FSB design approach. In this study, all of the major Shuttle elements (orbiter, external tank [ET]), solid rocket booster (SRB), launch and landing, and motor) were involved in assessing the potential implications of the FSB on each of their components. The primary emphasis was to assess the feasibility of the FSB eliminating RTLS by achieving TAL from the pad for a single Space Shuttle main engine (SSME) out. Another key aspect of the Phase A study was to determine the development cost to qualify an FSB and what the schedule associated with that qualification would be.

The study did confirm the feasibility of developing an FSB with minimal and manageable impacts on other Shuttle elements. It also showed that the FSB enabled the Shuttle to achieve TAL from the pad, thus eliminating RTLS. The study also identified trajectory enhancements that would be acceptable in an abort scenario and would improve the abort capability of the Shuttle. These trajectory enhancements were the precursor for the current OI-30 trajectory enhancements currently being implemented on the main stream Shuttle program. With these trajectory enhancements, the initial FSB configuration showed a limited capability to achieve abort-to-orbit (ATO) from the pad. The Phase A study also showed that the development costs would be approximately $1.1B and the development program would take approximately five years.

As a result of the potential afforded by the FSB shown in the Phase A study, Boeing and ATK Thiokol committed to expending their discretionary resources to mature the FSB concept to enhance its ability to achieve ATO. In this joint effort, performance modeling tools were developed that allowed a more accurate assessment of the FSB's ability to enhance abort modes, including identifying any potential load indicator violations resulting from the additional performance afforded by the FSB and other Shuttle elements. This model refinement also allowed Boeing to provide ATK Thiokol with idealized thrust profiles to more efficiently refine SRB grain designs.

The basic SRB configuration was also refined to more effectively meet the ATO goal (Figure 1). Notice that the primary aspect of the FSB is the addition of a new center segment to provide additional thrust and impulse. As a result of increasing the total impulse, it became necessary to design a new nozzle to ensure that the pressure capability of the current case hardware was maintained as well as to provide the necessary increase in thrust to meet mission needs. This new nozzle had a larger throat diameter to accommodate the increased mass flow rate associated with the added center segment.

By adding a center segment, the forward attach location to the ET is now on the external surface of the forward motor cylinder, as opposed to the previous condition where the ET was attached to the forward skirt. Since the forward skirt no longer needs to transmit the loads from the SRB to the ET, a new simpler lightweight forward skirt was designed. As a result of adding an additional center segment, the inert weight of the SRBs after separation was increased. Therefore, to maintain the same impact velocity of the SRB when it enters the ocean, a new larger diameter parachute was designed.

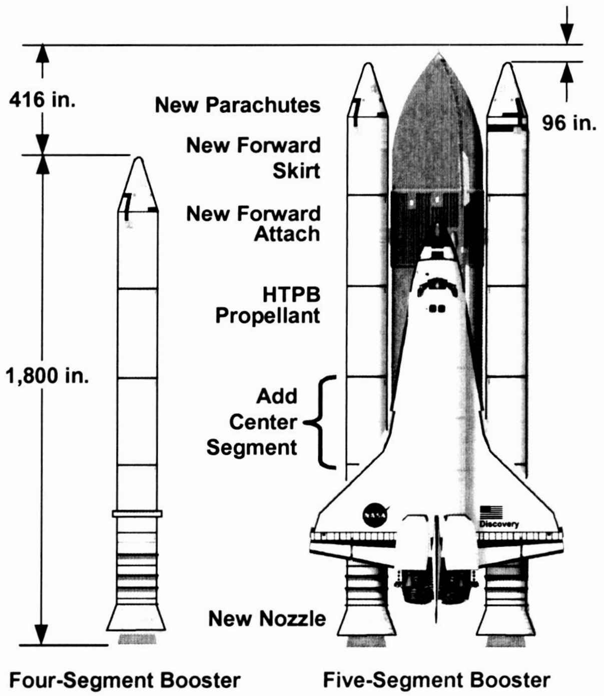


Figure 1. FSB Configuration

To achieve the desired thrust profile to match system constraints and accommodate the increased performance capability of the FSB, the forward segment grain design, inhibitor heights, and propellant burn rate had to be changed. The FSB refinement studies conducted by Boeing and ATK Thiokol indicated an increased probability of achieving ATO with the addition of an FSB and increasing the thrust level on the SSMEs. This refined assessment confirmed earlier results showing that the FSB in conjunction with SSME throttle setting increases could provide ATO from the pad with a single SSME out.

These results were sufficiently encouraging, such that NASA funded an additional study effort involving all of the Shuttle element contractors. This new study effort was to evaluate what would be the best option that combined improvements from all the various elements that maximize the potential of achieving ATO while minimizing the cost and schedule associated with achieving that goal.

In the initial Phase A study, the performance margins utilized were identical to those currently flown on nominal Shuttle flights. Since there are going to be changes to the trajectory constraints as well as SRB design and other element design considerations, it was determined that increased margins would be appropriate as future studies were conducted. Table 1 summarizes the increased performance margins that were applied in the evaluations conducted as part of this study activity. Figure 2 summarizes the abort trajectory enhancements utilized as part of this study activity. Notice that the

Table 1. ATO Performance Protection Deltas

ATO Performance Protection		
• ATO FPR (FSB configuration delta)		1,432 lb
• Current protection	2,268 lb	
• Proposed FSB	3,700 lb	
• FSB design uncertainty and weight margin		2,500 lb
• FSB mass properties	300 lb	
• Thrust shape	1,500 lb	
• ET mode	700 lb	
• RSRM reconstruction performance adjust		2,000 lb
• 1.1% Isp degradation (as done today)		
Program Protection		
• Match current ISS capability (above ISS PRM)		3,100 lb
• Managers reserve	2,500 lb	
• 5 min ISS window	600 lb	
	TOTAL	**9,100 lb**

FSB Phase A Study was the impetus for the abort enhancements currently being implemented as part of OI-30. A summary of the basic trade space considerations is also shown in Figure 2.

For the SRB itself we looked at three different lengths. The initial length was the same five-segment configuration from the initial Phase A study. Additional increases in length of 65 and 96 in. were also evaluated. An additional SRB consideration was to evaluate the changing of the propellant formulation from the current Shuttle formulation (PBAN: polybutadiene acrylonitrile/acrylic acid copolymer) to a more modern solid propellant formulation (HTPB: hydroxyl-terminated polybutadiene). An additional trajectory enhancement was evaluated using a heads-up trajectory profile as opposed to the currently utilized heads-down approach. The study also evaluated varying the levels of SSME power setting for no fail and intact abort missions. Changing the SSME fuel-to-oxidizer mixture ratio (MR) from 6.032 to 5.85 was also evaluated.

An additional consideration included in the trade study was off-loading propellant from the ET over the range of 40,000 to 200,000 lb. The propellant off-load is a major enhancement consideration relative to improving abort modes. The reason that propellant is off-loaded is that, with the added performance from increased SRB size and increased SSME power level setting, maximizing abort capability is more important than increasing payload performance. This is because the payload performance is already constrained by the down weight capability of the orbiter. When maximizing abort characteristics, increasing the thrust-to-weight ratio at liftoff is more important than total impulse and thus the off-load of the SSME propellant ended up being a major enhancement to abort capability.

PROPELLANT OFF-LOAD

A summary of the effects of propellant off-loading is shown in Figure 3. Notice that the implications of off-load vary depending on which abort consideration is trying to be maximized. The upper two curves address the effect of propellant off-loading on press-to-abort (PTA), which is the same as ATO. The lower curves show the implications on PTM (press-to-main engine cutoff (MECO)), which is essentially aborting to the destination orbit. In both cases the sensitivity of SSME throttle setting on propellant off-load is also included looking at both 112 and 113 percent SSME throttle levels. Notice that the ATO capability is maximized at an off-load of approximately 140,000 lb of main engine propellant. Also, notice that in this particular study all options are achieving ATO and determining what the propellant margin is while achieving ATO. In other words, in Figure 3 at a 113 percent SSME throttle setting an off-load of 140,000 lb, the propellant margin associated with meeting ATO is approximately 8,000 lb. This is somewhat short of the desired goal of 9,100 lb of margin.

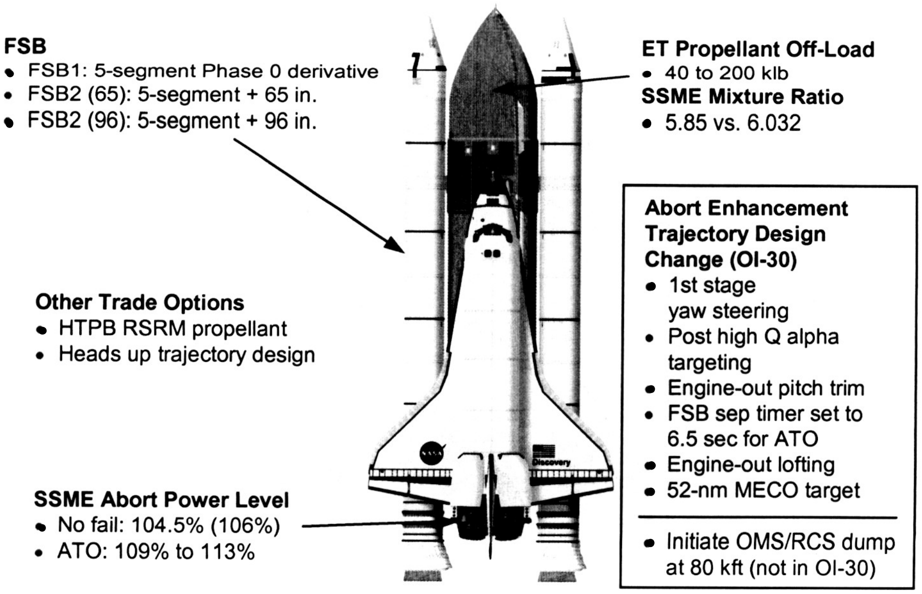
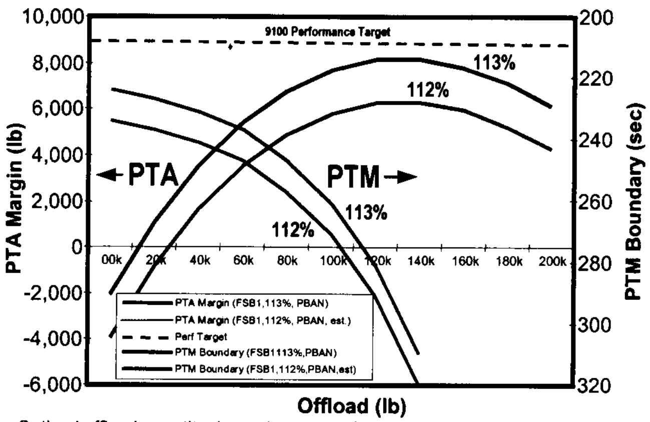
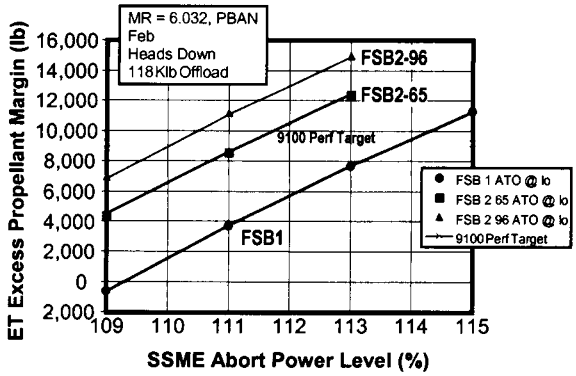


Figure 2. Trajectory Enhancements and Trade Options



Optimal offload quantity dependent on trade between earlier PTM and PTA margin

Figure 3. Example of PTA vs. PTM Trade



ATO Performance (current capability) for FSB1 SSMEs at 113% PL, FSB2-65 at 111%, FSB2-96 at 109% based on ASTRO 6 DOF

ATO performance for other power levels based on ASTRO 3 DOF trends

Figure 4. ATO Liftoff Performance vs. Abort Power Level

SSME THROTTLE SETTING

The effect of SSME throttle setting on abort capability is shown in Figure 4. All three basic FSB configurations were evaluated. The three configurations again were FSB1, which is a notional five-segment configuration similar to that shown in Figure 1 with the standard Shuttle propellant. FSB2 has additional length increases beyond five-segment configuration looking at an additional 65 and 96 in., respectively. Notice that to achieve ATO with the desired 9,100-lb propellant margin, the basic five-segment configuration with Shuttle propellant would require an SSME throttle setting of just under 114 percent. Similarly, with the 65-in. increase, the SSME throttle setting would need to be slightly over 111 percent and with the 96-in. increase over the standard five-segment configuration would require a 110 percent SSME throttle setting. Notice that all of the SSME throttle setting sensitivity studies shown in Figure 4 assumed a MR of 6.032.

To provide a better understanding of the overall implications of changing the SSME throttle setting, a summary of the effort required to certify the SSME to various increased power setting levels is shown in Table 2. The table includes a summary of the implications on reliability risk, structural capability, development schedule, and development cost. The most significant change would be adjusting the MR from 6.032 to 5.85 and increasing the throttle setting to a 113 percent for abort missions. In all cases, the certified power level is 2 percent lower than what the engine would be tested to during the certification process. In other words, a 113 percent certified power level would require testing at 115 percent.

EXTERNAL TANK

The implications of propellant off-loading on the ET design were also evaluated. In the initial Phase A study the structural and thermal implications associated with going to a basic FSB resulted in an increase in inert weight due to increased structure and thermal protection system, of approximately 650 lb. During this study, implications of various off-loading and design changes were assessed against that initial increased weight allocation. Notice that three basic options were looked at (Figure 5), changing the float control valve (FCV) at both a 5.85 and 6.032 MR as well as going to a fixed orifice (FO) at a 5.85 MR were evaluated. Going to a 5.85 MR with a modified FCV resulted in the best performance option, which essentially reduced the structural and thermal weight allocation from the initial 650

Performed Preliminary Structural Assessment

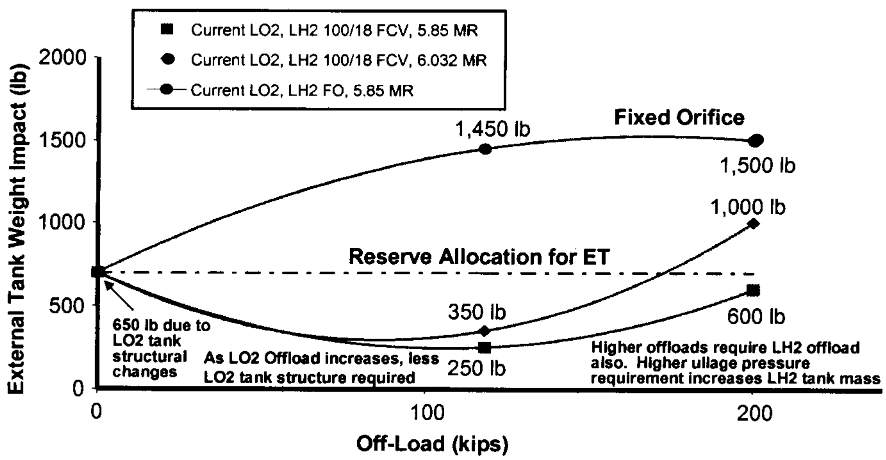


Figure 5. Propellant Off-Load: Structural Results

Table 2. SSME Power Level Certification

ATO Power Level	MR	Structural Assessment	Feasibility	Certification Type	Certification Hardware Impact	Schedule
109%	6.032	Certified For Flight	1.0	N/A	N/A	N/A
109%	5.85	Enveloped by normal engine operation variation	1.0	C	Minor New Nozzle	10 months 13 Demo/Dev 11 Cert/1 Eng
111%	6.032	Significant time at 111%	1.0	C	Minor New Nozzle	10 months 13 Demo/Dev 11 Cert/1 Eng
111%	5.85	Significant time at 111% 5.85 MR minor impact	0.95	B	Minor New Nozzle	12 months 13 Demo/Dev 11 Cert/2 Eng
113%	6.032	Okay for demonstration testing	0.9	B	Minor New Nozzle	12 months 13 Demo/Dev 11 Cert/2 Eng
113%	5.85	Okay for demonstration testing	0.8	A	Minor + New Powerhead	14 months 13 Demo/Dev 22 Cert/2 Eng

lb down to 250 lb, which was a 400-lb improvement. As in the original Phase A study, there are no major show-stopping implications associated with ET modifications to accommodate any of the FSB configurations.

BOOSTER ELEMENT

During this evaluation, the Shuttle SRB element reassessed the implications of an FSB on all of the solid SRB element hardware. A summary of those implications is shown in Figure 6. The current separation bolt on the Shuttle system at the ET-to-SRB interface has a slight negative margin. In going to the lengthened FSB configuration, with increased thrust, that negative margin is aggravated beyond the level of acceptability for flight. As such, for the FSB the forward separation bolt will have to be redesigned.

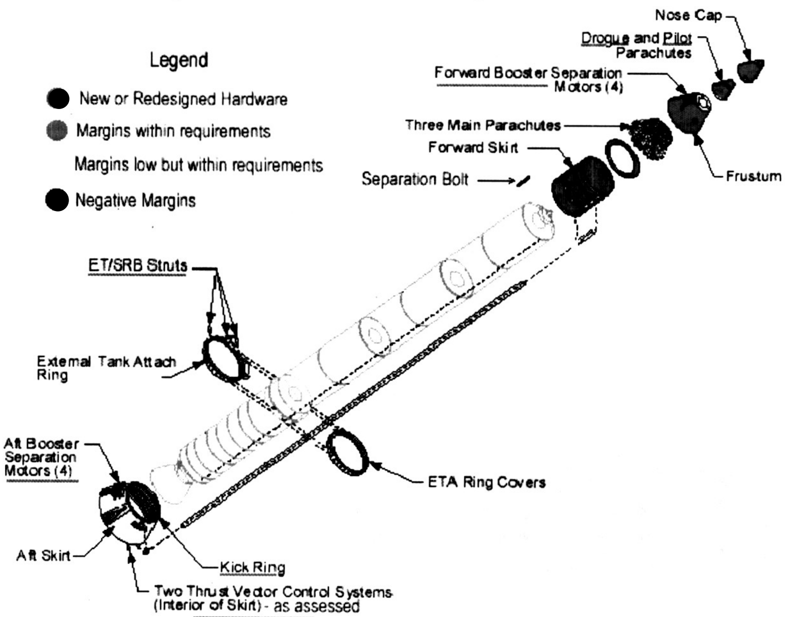


Figure 6. FSB SRB Element Assessment Overview

In the process of redesigning the separation bolt, it will be configured such that it will return to a positive margin condition. This will be a net improvement in reliability of the five-segment relative to the current SRB configuration. Figure 7 shows notionally that as you increase the length of the FSB, the basic load that needs to be accommodated by the separation bolt increases somewhat, but not beyond the capability of being accommodated with known separation bolt technologies.

In the initial Phase A study, the ability of the thrust vector control system to accommodate the increased thrust level and torque of the new FSB system and nozzle was evaluated in the no-fail or nominal condition. In that particular scenario, the existing thrust vector actuation (TVA) system and components are adequate to accommodate the FSB modifications.

Future studies will need to look at the one auxiliary power unit out condition to determine the acceptability of the TVA system under the more severe off-nominal

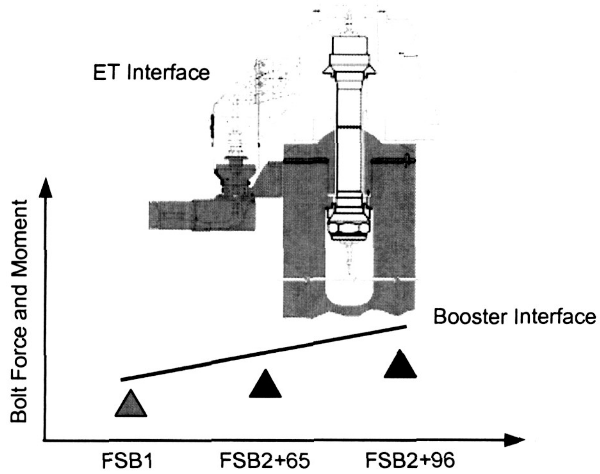


Figure 7. Forward Separation Bolt loads

operation requirement. Fortunately, the extended burn time of the FSB will be evaluated as part of the upcoming engineering test motor ETM-3 test and the ability of the TVA system to accommodate the longer burn time will be verified as part of that demonstration test. Figure 8 shows notionally that as the length of the FSB increases, thus increasing the burn time, the overall demands on TVA system capabilities increase somewhat as a function of that increase in length.

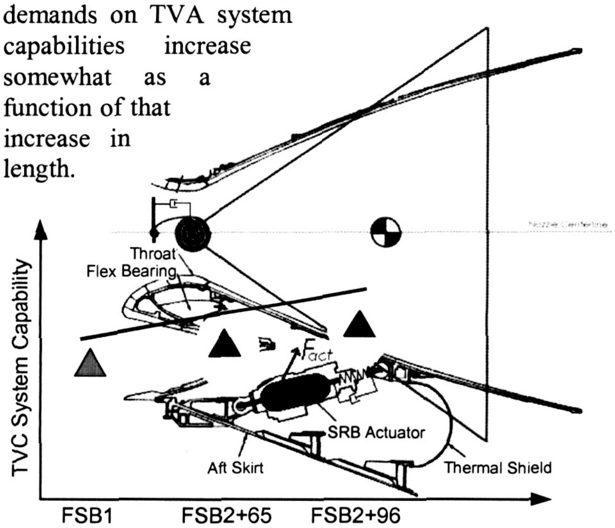


Figure 8. FSB Actuator Evaluation

Another consideration for the SRB components was the impact of increasing the SRB length on the re-entry system design. By going to an FSB, the overall inert weight of the system increases and the necessity to maintain impact velocity during recovery becomes more demanding. As such, the diameter of the parachute will need to be increased to compensate for the increased inert weight of the larger FSB. During the Phase A study, new parachute designs and sizes were evaluated and found capable of compensating for the increased inert weight. The increased parachute size can still be packaged within the available volume within the existing forward frustum.

The evaluation of the re-entry dynamics conducted during this phase of the evaluation indicated that there was an increase in the maximum dynamic pressure during re-entry compared to earlier FSB Phase A studies. This will need to be evaluated in future qualification efforts, but does not appear to be a major design or technology driver. Any increase in SRB length beyond the current five-segment configuration appears to have a minimal implication on the re-entry trajectory and dynamics as shown in Figure 9.

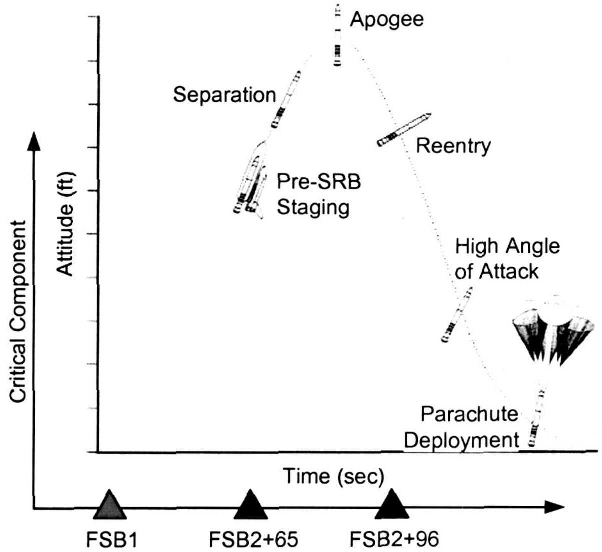


Figure 9. FSB Re-entry Trajectory

The vibro-acoustic environment associated with changing the reusable solid rocket motor (RSRM) configuration to a five-segment configuration is more severe as shown in Figure 10. Notice that the existing SRB is enveloped within the ET shockwave, but as you go to the initial five-segment configuration (FSB0), a portion of

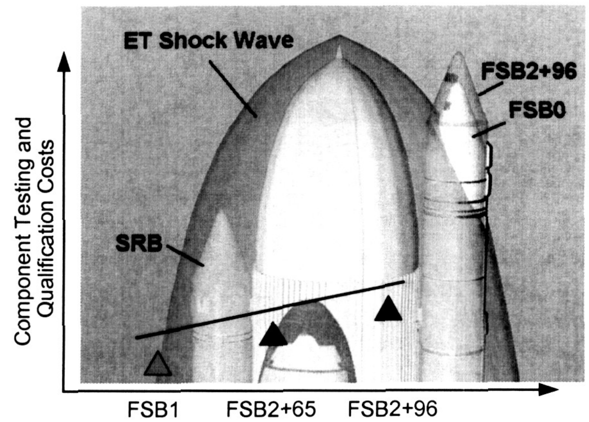


Figure 10. FSB Vibro-Acoustic Effects

the forward frustum and some of the forward skirt penetrates beyond the ET shockwave environment, which creates a more severe vibro-acoustic environment relative to today's condition. Notice that as the SRB increases in length beyond the basic five-segment configuration, the vibro-acoustic environment becomes somewhat more severe as a greater portion of the forward skirt and frustum penetrate beyond the ET shockwave.

MOTOR

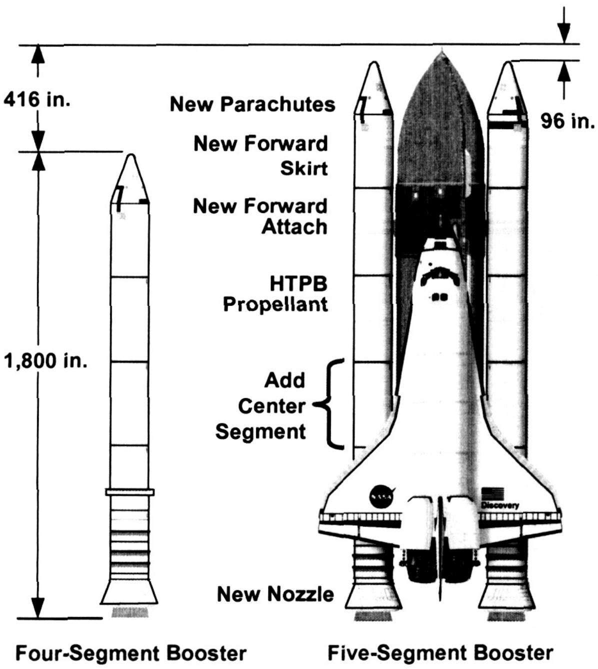
A summary of the relative performance comparisons between the FSB and the existing reusable solid rocket motor (RSRM) is shown in Figure 11. Notice that this is a direct comparison using the same propellant in the FSB as in the RSRM. In this case the thrust level increases by ~500,000 lb and the burn time is increased by approximately 6 seconds. The thrust-time figure shows the increase in total impulse associated with the FSB that can be used as added capability to support enhancing abort modes as well as providing flexibility to increase payload capability or other desirable mission attributes.

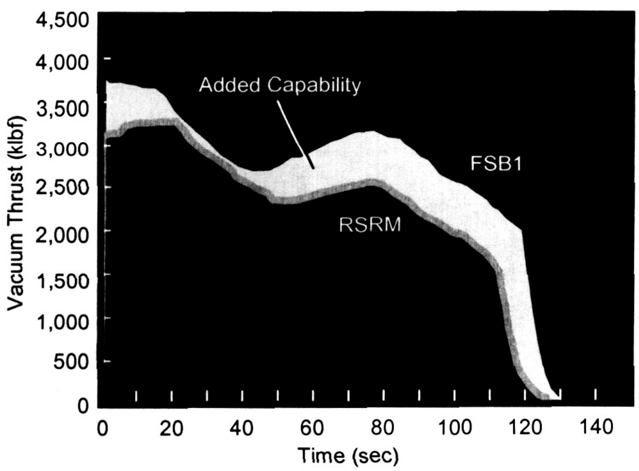
As mentioned earlier, the key characteristics in the motor that have been modified are 1) the addition of a center segment to provide the added impulse, 2) a modification of the forward segment to accommodate the external attach of the SRB to the ET, 3) a new forward skirt that does not have the ET attach features included, and 4) a new nozzle that facilitates the increase in the mass flow rate associated with the added segment and maintains the same pressure capability of the metal hardware pressure vessel (also incorporating design features that improve the reliability of the nozzle). A general summary of the motor implications is contained in Figure 12.

The most significant implications have to do with the potential of changing propellant from the current Shuttle formulation (PBAN) to a more modern propellant formulation (HTPB). The propellant formulation change would be an option to increase performance capability for each of the basic length configurations evaluated. Converting to the more energetic HTPB propellant would require additional thermal analysis for the ET and orbiter to ensure no major thermal margins are being violated or determining what additional thermal protection system options would be required with a more severe thermal environment. Initial analyses conducted in this study indicated that all existing component thermal margins could be maintained with acceptable changes within existing available technical options.

LAUNCH AND LANDING

The launch and landing personnel conducted an assessment to evaluate the launch processing implications of the various SRB configurations that were evaluated. This was essentially an update to the processing evaluation conducted in the earlier Phase A study. A summary of implications is shown in Table 3.

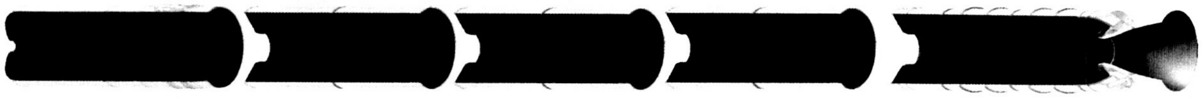




Booster Performance

	5-Segment	4-Segment
Max Thrust (lbf)	3,920,000	3,330,000
Max Pressure (psia)	1,066	1,016
Burn Time (sec)	129.6	123.4

Figure 11. 4-Segment vs. 5-Segment Booster Performance Comparison



Technical Complexity
Pros
- Good overall match of thrust time trace
- Shortest motor design

Cons
- Increased motor pressure drop
- Grain structural safety factors (SF) challenged

Mitigation Options
- Split few segment into 2 casting segments
- Full length fins with center perforated section
- Accept performance reduction for increased SF
- Adopt HTPB propellant

Life Cycle Costs
Pros
- Minimizes amount of new case hardware
- No static test stand

Cons
- May require HTPB propellant development and qualification plus impacts to ATK Thiokol facilities. Plume heating to be characterized
- Increased Kennedy Space Center bore operations for fin support removal

Schedule
Pros
- Minimizes amount of new case hardware
- No static test stand modifications
- No static test stand modifications required

Cons
- Technical complexity could dictate additional static test(s)

Reliability
Pros
- FSB nozzle
- Potential for least field joints

Cons
- Additional field joint possibly required to mitigate grain SF issues

ATK Thiokol

Figure 12. FSB Assessment

The least significant implications are associated with utilizing the FSB1 configuration. For this configuration, the SRB serial processing time would be increased by five days and result in modest facility modification cost. The FSB1 configuration would still be capable of supporting a six-flight-per-year manifest. The other increased length configurations add a shorter one-third-length segment that would need to be processed at the launch facility. The increased handling associated with processing this smaller added segment would increase the serial processing time to 11 days and minimal increase in the facility modification cost.

In order to narrow down the potential combinations of options into a more manageable number for evaluation, a complexity matrix was generated (Table 4). The intent of this matrix was to identify which performance enhancement options would provide the least risk and would definitely be considered for incorporation. Notice that options one, two, and three offer low risk in all categories of consideration and, thus, were incorporated

Table 3. Launch Processing Comparisons

Factor (cost and Schedule No.s Delta from 4-segment)	5-Segment Phase A Derivative	6-Segment (+65)	6-Segment (+96)	Comments
Processing Timeline Impact	+5 Days Serial to SRB Processing	+11 Days Serial to SRB Processing	+11 Days Serial to SRB Processing	• Additional segment + closeouts • Two days per segment • One day more for the additional joint closeouts
Manifest Impact	6 flights/year	6 flights/year	6 flights/year	• Meet flight rate buy will not meet minimum launch interval requirements with current facility and processing ground rules
Facilities/GSE Impact (development) Rough Order-of-Magnitude Cost				• RPSF: Addition of 3rd surge facility • Vehicle Assembly Building: High Bay 1 & 3 access platforms • MLP: Tall service mast, sound suppression system • Pads: Gaseous oxygen vent hood, sound suppression system • Stacking Facility: Not included
Headcount Impact	+12	>50 Needs additional study	>50 Needs additional study	• FSB stacking requires 7/3 shifting/staffing over a sustained period

Table 4. Option Summary Comparison

Studies show additional performance is required above the 5-segment booster upgrade

Options	Risk and Reliability	Technical Complexity	Cost and Cost Uncertainties
1. Mixture Ratio 5.85	Low	Low	Low
2. Offloads of 41 or 119 klb	Low	Low	Low
3. 111% ATO Throttle Levels	Low	Low	Low
4a. 113% ATO Throttle Levels	Med-High	Low	Med-High
4b. HTPB Propellant	Med-High	Med-High	Med-High
4c. Roll to Heads Up	Med-High	Med-High	Low
4d. Six Segments (FSB2)	Med-High	Med-High	Med-High

Options 1 and 2 selected as a baseline for all configurations (i.e., 6.032 MR and offloads of zero and 153 klb were eliminated

in all of the options for final evaluation. As a result of this risk evaluation filtering process, two basic configurations were selected as being the most desirable. All configurations selected provided ATO capability (Figure 13) with the desired performance margin.

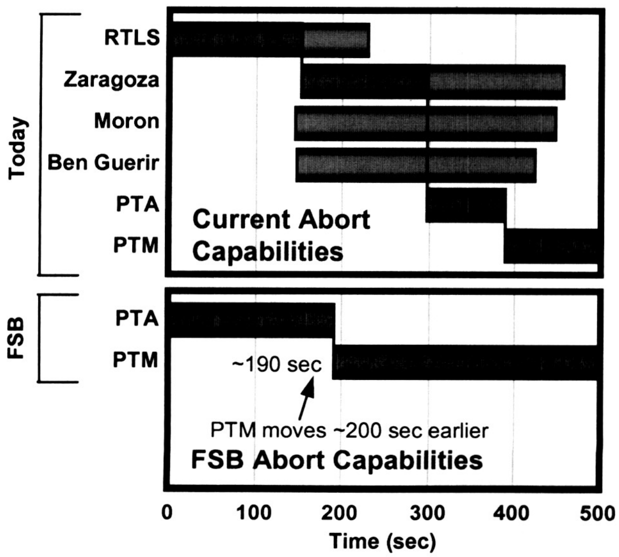


Figure 13. Shuttle Abort Enhancements With FSB

The most desirable configuration was a motor with the FSB1 length, an SSME MR of 5.85, an ET off-load of somewhere between 41,000 and 118,000 lb, an SSME throttle setting of 111 percent, and HTPB propellant. The next most desirable options were 1) additional FSB length (+88 in.), using PBAN propellant, an SSME throttle setting to 111 percent and 5.85 MR, and an off-load of 118,000 lb of propellant; or 2) using a MR of 5.85, an off-load of 118,000 lb of propellant, an SSME throttle setting of 113 percent and PBAN propellant (Table 5).

DEVELOPMENT COSTS

The total development cost for an FSB would be approximately $1.3B (with a recurring cost) at a flight rate of six per year for 13 years, adding another $600M for a total life cycle cost of just under $2B.

Table 5. Potential Back-off Options

If issues arise with HTPB during Phase 4 assessments then the other FSB1 configuration could be selected with minimum impact to the project

- Reduced performance margin to 8,800 lb
  - FSB1: PBAN, 118k lb off-load, 113%, and 5.85 MR
- Reduced performance margin to 6,000 lb
  - FSB1: PBAN, 118k lb offload, 112%, and 5.85 MR

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ACRONYMS

SRB ....solid rocket booster
ATO............abort-to-orbit
DOF............degree of freedom
ET................external tank
FCV............float control valve
FO................fixed orifice
FPR.............flight performance reserve
FSB.............five-segment booster
HTPB...........hydroxyl-terminated polybutadiene
Isp................specific impulse
ISS...............International Space Station
LCC.............life cycle cost
LH_2..............liquid hydrogen
LO_2..............liquid oxygen
MECO ....main engine cutoff
MR...............mixture ratio
OMS/RCS....orbital maneuvering system/reaction control system
PBAN..........polybutadiene acrylonitrile/acrylic acid copolymer
PRA.............probability risk assessment
PRM ....performance reference mission
RSRM..........reusable solid rocket motor
PTA.............press to abort
PTM............press to MECO
RTLS...........return to launch site
SRB.............solid rocket booster
SSME ....Space Shuttle main engine
TAL............transoceanic abort landing
TPS.............thermal protection system
TVA............thrust vector actuation

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